# T-odd effects in photon-jet production at the Tevatron

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The angular distribution in photon-jet production in $p\,\bar{p} \to \gamma\,\mathrm{jet}\,X$ is studied within a generalized factorization scheme taking into account the transverse momentum of the partons in the initial hadrons. Within this scheme an anomalously large $\cos 2\phi$ asymmetry observed in the Drell-Yan process could be attributed to the T-odd, spin and transverse momentum dependent parton distribution function $h_1^{\perp\,q}(x, \boldsymbol{p}_\perp^2)$. This same function is expected to produce a $\cos 2\phi$ asymmetry in the photon-jet production cross section. We give the expression for this particular azimuthal asymmetry, which is estimated to be smaller than the Drell-Yan asymmetry but still of considerable size for Tevatron kinematics. This offers a new possibility to study T-odd effects at the Tevatron.

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## I. INTRODUCTION

It is well-known that the angular distribution of Drell-Yan lepton pairs displays an anomalously large $\cos 2\phi$ asymmetry. This was experimentally investigated using $\pi^-$ beams scattering off deuterium and tungsten targets at center of mass energies of order 20 GeV [1, 2, 3]. A next-to-leading order (NLO) analysis in perturbative QCD (pQCD) within the standard framework of collinear factorization failed to describe the data [4]. More specifically, the observed violation of the so-called Lam-Tung relation [5, 6, 7], a relation between two angular asymmetry terms, could not be described. The NLO pQCD result is an order of magnitude too small and of opposite sign. This has prompted much theoretical work [4, 8, 9, 10, 11, 12, 13, 14, 15, 16], offering explanations that go beyond the framework of collinear factorization and/or leading twist perturbative QCD.

More recently, $p\,d$ Drell-Yan scattering was studied in a fixed target experiment ($\sqrt{s} \approx 40$ GeV) at Fermilab [17]. The angular distribution does not display a large $\cos 2\phi$ asymmetry, indicating that the effect that causes the large asymmetry in $\pi^- N$ scattering is probably small for nonvalence partons. For this reason one would like to investigate $p\,\bar{p}$ scattering, which is expected to be similar to the $\pi^- N$ case (an expectation supported by model calculations [10, 14, 18]). It is an experiment that could be done at the planned GSI-FAIR facility. It can in principle also be done at Fermilab, although the energy of the collisions is so much higher ($\sqrt{s} = 1.96$ TeV) that the Drell-Yan asymmetry may be quite different in magnitude, possibly much smaller at very high invariant mass $Q$ of the lepton pair. Nevertheless, it would be interesting to see if NLO pQCD expectations hold at those energies. Recently, such a study of the angular distribution was done for $W$-boson production at the Tevatron and a nonzero result compatible with NLO pQCD [19, 20] was obtained [21]. This may likely be due to the fact that chirality flip effects, such as the T-odd effect to be discussed here, do not contribute to the $\cos 2\phi$ angular distribution [22, 23]. For neutral boson production they do contribute however and therefore could lead to quite a different result. This remains to be investigated.

In this paper we consider an asymmetry in the process $p\,\bar{p} \to \gamma$ jet $X$ that potentially probes the same underlying mechanism and could have certain advantages over Drell-Yan. This photon-jet production process has already been studied experimentally in the angular integrated case at the Tevatron [24]. Here we will calculate the angular dependence within the framework as employed in Ref. [16], where transverse momentum and spin dependence of partons inside hadrons is included[1]. In that case a nontrivial polarization-dependent quark distribution (denoted by $h_1^{\perp\,q}$) appears, which offers an explanation for the anomalous angular asymmetry in the Drell-Yan process. The new asymmetry is proportional to the analyzing power of the Drell-Yan $\cos 2\phi$ asymmetry at the scale set by the transverse momentum of the photon or the jet. The latter asymmetry is expected to decrease with increasing scale [26], but as

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[1] Photon-jet angular correlations in $p\,p$ and $p\,\bar{p}$ collisions have also recently been studied in Ref. [25] using the $k_t$-factorization approach applicable at small $x$, where gluon-gluon scattering dominates.

we will demonstrate the proportionality factor increases, leading one to expect a significant asymmetry also at higher energies.

In Section II we discuss the theoretical framework and the expected contributions to the new asymmetry. In Section III we study the phenomenology of this asymmetry, using typical Tevatron kinematics and cuts. We end with a summary of the results and the required measurement.

## II. THEORETICAL FRAMEWORK: CALCULATION OF THE CROSS SECTION

We consider the process

$$h_1(P_1)+h_2(P_2)\to\gamma(K_\gamma)+\text{jet}(K_j)+X\,, \tag{1}$$

where the four-momenta of the particles are given within brackets, and the photon-jet pair in the final state is almost back-to-back in the plane perpendicular to the direction of the incoming hadrons. To lowest order in pQCD the reaction is described in terms of the partonic two-to-two subprocesses

$$q(p_1)+\bar q(p_2)\to\gamma(K_\gamma)+g(K_j)\,,\qquad\text{and}\qquad q(p_1)+g(p_2)\to\gamma(K_\gamma)+q(K_j)\ . \tag{2}$$

We make a lightcone decomposition of the hadronic momenta in terms of two light-like Sudakov vectors $n_+$ and $n_-$, satisfying $n_+^2=n_-^2=0$ and $n_+\cdot n_-=1$:

$$P_1^\mu=P_1^+n_+^\mu+\frac{M_1^2}{2P_1^+}n_-^\mu\ ,\qquad\text{and}\qquad P_2^\mu=\frac{M_2^2}{2P_2^-}n_+^\mu+P_2^-n_-^\mu\ \ . \tag{3}$$

In general $n_+$ and $n_-$ will define the lightcone components of every vector $a$ as $a^\pm\equiv a\cdot n_\mp$, while perpendicular vectors $a_\perp$ will always refer to the components of $a$ orthogonal to both incoming hadronic momenta, $P_1$ and $P_2$. Hence the partonic momenta ($p_1$, $p_2$) can be expressed in terms of the lightcone momentum fractions ($x_1$, $x_2$) and the intrinsic transverse momenta ($p_{1\perp}$, $p_{2\perp}$), as follows

$$p_1^\mu=x_1P_1^+n_+^\mu+\frac{m_1^2+\boldsymbol{p}_{1\perp}^2}{2x_1P_1^+}n_-^\mu+p_{1\perp}^\mu\ ,\qquad\text{and}\qquad p_2^\mu=\frac{m_2^2+\boldsymbol{p}_{2\perp}^2}{2x_2P_2^-}n_+^\mu+x_2P_2^-n_-^\mu+p_{2\perp}^\mu\ . \tag{4}$$

We denote with $s$ the total energy squared in the hadronic center-of-mass (c.m.) frame, $s=(P_1+P_2)^2=E_{\text{c.m.}}^2$, and with $\eta_i$ the pseudo-rapidities of the outgoing particles, *i.e.* $\eta_i=-\ln\big(\tan(\frac{1}{2}\theta_i)\big)$, $\theta_i$ being the polar angles of the outgoing particles in the same frame. Finally, we introduce the partonic Mandelstam variables

$$\hat s=(p_1+p_2)^2,\qquad\hat t=(p_1-K_\gamma)^2,\qquad\hat u=(p_1-K_j)^2, \tag{5}$$

which satisfy the relations

$$-\frac{\hat t}{\hat s}\equiv y=\frac{1}{e^{\eta_\gamma-\eta_j}+1}\ ,\qquad\text{and}\qquad-\frac{\hat u}{\hat s}=1-y\ . \tag{6}$$

Following Ref. [27] we assume that at sufficiently high energies the hadronic cross section factorizes in a soft parton correlator for each observed hadron and a hard part:

$$\begin{aligned}d\sigma^{h_1h_2\to\gamma\text{jet}X}\ =\ &\frac{1}{2s}\,\frac{d^3K_\gamma}{(2\pi)^3\,2E_\gamma}\,\frac{d^3K_j}{(2\pi)^3\,2E_j}\int dx_1\,d^2\boldsymbol{p}_{1\perp}\,dx_2\,d^2\boldsymbol{p}_{2\perp}\,(2\pi)^4\delta^4(p_1+p_2-K_\gamma-K_j)\\&\times\sum_{a,b,c}\ \Phi_a(x_1,p_{1\perp})\otimes\Phi_b(x_2,p_{2\perp})\otimes\,|H_{ab\to\gamma c}(p_1,p_2,K_\gamma,K_j)|^2\ ,\end{aligned} \tag{7}$$

where the sum runs over all the incoming and outgoing partons taking part in the subprocesses in (2). The convolutions $\otimes$ indicate the appropriate traces over Dirac indices and $|H|^2$ is the hard partonic squared amplitude, obtained from the cut diagrams in Figs. 1 and 2 [27]. The parton correlators are defined on the lightfront LF ($\xi\cdot n\equiv 0$, with $n\equiv n_-$ for parton 1 and $n\equiv n_+$ for parton 2); they describe the hadron $\to$ parton transitions and can be parameterized in terms of transverse momentum dependent (TMD) distribution functions. The quark content of an unpolarized hadron is described, in the lightcone gauge $A\cdot n=0$ and at leading twist, by the correlator [28]

$$\Phi_q(x,p_\perp;P)=\int\frac{d(\xi\cdot P)\,d^2\xi_\perp}{(2\pi)^3}\ e^{ip\cdot\xi}\,\langle P|\,\overline\psi(0)\,\psi(\xi)\,|P\rangle\,\big\rfloor_{\text{LF}}=\frac{1}{2}\left\{\,f_1^q(x,\boldsymbol{p}_\perp^2)\,\not{P}+ih_1^{\perp\,q}(x,\boldsymbol{p}_\perp^2)\,\frac{[\not{p}_\perp,\not{P}]}{2M}\right\}, \tag{8}$$

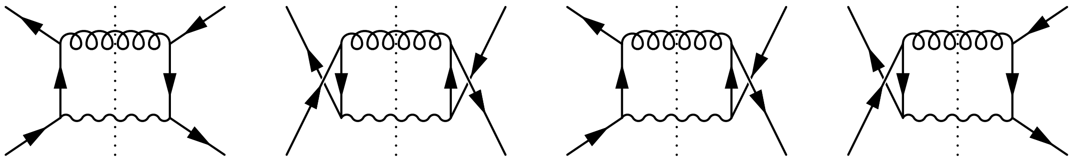

FIG. 1: Cut diagrams for the subprocess $q\bar{q} \to \gamma g$.

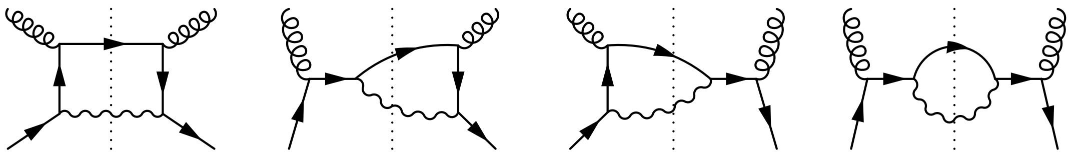

FIG. 2: Cut diagrams for the subprocess $qg \to \gamma q$.

where $f_1^q(x, \boldsymbol{p}_\perp^2)$ is the unpolarized quark distribution, which integrated over $\boldsymbol{p}_\perp$ gives the familiar lightcone momentum distribution $f_1^q(x)$. The time-reversal (T) odd function $h_1^{\perp q}(x, \boldsymbol{p}_\perp^2)$ is interpreted as the quark transverse spin distribution in an unpolarized hadron [28]. Below we will discuss the T-odd nature of this function and its consequences in more detail.

Analogously, for an antiquark,

$$\bar{\Phi}_q(x,p_\perp;P) = -\int \frac{d(\xi{\cdot}P)\, d^2\xi_\perp}{(2\pi)^3}\, e^{-ip\cdot\xi}\, \langle P|\, \overline{\psi}(0)\, \psi(\xi)\, |P\rangle \,\big\rfloor_{\rm LF} = \frac{1}{2}\left\{ f_1^{\bar{q}}(x,\boldsymbol{p}_\perp^2)\, \not{P} + i h_1^{\perp\,\bar{q}}(x,\boldsymbol{p}_\perp^2)\, \frac{[\not{p}_\perp, \not{P}]}{2M} \right\}. \tag{9}$$

The gluon correlator in the lightcone gauge is given by [29]

$$\begin{aligned} \Phi_g^{\mu\nu}(x,p_\perp;P) &= \frac{n_\rho\, n_\sigma}{(p{\cdot}n)^2}\int \frac{d(\xi{\cdot}P)\, d^2\xi_\perp}{(2\pi)^3}\, e^{ip\cdot\xi}\, \langle P|\, \mathrm{Tr}\left[\, F^{\mu\rho}(0)\, F^{\nu\sigma}(\xi)\,\right] |P\rangle \,\big\rfloor_{\rm LF} \\ &= \frac{1}{2x}\left\{ -g_\perp^{\mu\nu}\, f_1^g(x,\boldsymbol{p}_\perp^2) + \left(\frac{p_\perp^\mu p_\perp^\nu}{M^2} + g_\perp^{\mu\nu}\frac{\boldsymbol{p}_\perp^2}{2M^2}\right) h_1^{\perp\, g}(x,\boldsymbol{p}_\perp^2)\right\}, \end{aligned} \tag{10}$$

with $g_\perp^{\mu\nu}$ being a transverse tensor defined as

$$g_\perp^{\mu\nu} = g^{\mu\nu} - n_+^\mu n_-^\nu - n_-^\mu n_+^\nu\,. \tag{11}$$

The function $f_1^g(x,\boldsymbol{p}_\perp^2)$ represents the usual unpolarized gluon distribution, while the T-even function $h_1^{\perp\, g}(x,\boldsymbol{p}_\perp^2)$ is the distribution of linearly polarized gluons in an unpolarized hadron. We include it here because it potentially contributes to the observable of interest. However, it will turn out to yield a power-suppressed contribution.

In the above expressions $h_1^{\perp\, q}$ appears as the T-odd part in the parametrization of the correlator $\Phi_q$. For distribution functions, however, such a T-odd part is intimately connected to the gauge link that appears in the correlator $\Phi_q$ connecting the quark fields. This gauge link is process-dependent and as a result, T-odd functions can appear with different factors in different processes. The specific factor can be traced back to the color flow in the cut diagrams of the partonic hard scattering. In situations in which only one T-odd function contributes this has been analyzed in detail for the process of interest and related processes, cf. e.g. Refs. [30, 31]. It leads to specific color factors multiplying the T-odd distribution function. In the case of single spin asymmetries (SSA) one T-odd function appears, which could be the distribution function $h_1^{\perp\, q}$. Taking the appearance in the case of leptoproduction as reference (having a factor $+1$ for the $\gamma^* q \to q$ subprocess), one finds appearance with a different factor in Drell-Yan scattering (factor $-1$ for $q\bar{q} \to \gamma^*$ subprocess [32, 33, 34]) or yet another factor for the appearance in the SSA in photon-jet production (factor $(N^2+1)/(N^2-1)$ for all contributions shown in Figs 1 and 2 [27]). In the $\cos 2\phi$ asymmetry in Drell-Yan and in photon-jet production the situation is different because a product of two T-odd functions arises ($h_1^{\perp q}\, h_1^{\perp \bar{q}}$). As we will discuss the factors are in both cases simply $+1$, which fixes the relative sign of the asymmetries in the two processes to be $+1$.

The factor in photon-jet production arises in the following way. All diagrams have only two color flow contributions with relative strength $N^2$ and $-1$. Color averaging in the initial state gives the usual color factors $(N^2-1)/N^2$ for

the $q\bar{q} \to \gamma g$ process and $(N^2-1)/N(N^2-1) = 1/N$ for the $qg \to \gamma q$ process. Including gauge links in the TMD correlators one schematically has

$$q\bar{q} \to \gamma g : \qquad \frac{N^2}{N^2-1}\, \Phi_q^{[+(\Box^\dagger)]} \otimes \overline{\Phi}_q^{[+^\dagger(\Box)]} \otimes |H|^2 \otimes \Delta_g^{[-][-^\dagger]} - \frac{1}{N^2-1}\, \Phi_q^{[-]} \otimes \overline{\Phi}_q^{[-^\dagger]} \otimes |H|^2 \otimes \Delta_g^{[-][-^\dagger]}, \tag{12}$$

$$qg \to \gamma q : \qquad \frac{N^2}{N^2-1}\, \Phi_q^{[-(\Box)]} \otimes \overline{\Phi}_g^{[+][-^\dagger]} \otimes |H|^2 \otimes \Delta_q^{[-^\dagger]} - \frac{1}{N^2-1}\, \Phi_q^{[+]} \otimes \overline{\Phi}_g^{[+][-^\dagger]} \otimes |H|^2 \otimes \Delta_q^{[-^\dagger]}, \tag{13}$$

where the correlators now include gauge links, $\Phi^{[+]} \sim \langle \overline{\psi}(0)\, U^{[+]} \psi(\xi)\rangle$ or $\Phi_g^{[+][-^\dagger]} \sim \langle F(0) U^{[+]}(0,\xi) F(\xi) U^{[-]\dagger}\rangle$, etc. The gauge links $U^{[\pm]}$ are the future and past-pointing ones in which the path runs via lightcone $\pm\infty$, respectively. The $(\Box)$ contributions indicate the presence of a $\frac{1}{N}\mathrm{Tr}(U^{[+]}U^{[-]\dagger})$ term. Following Ref. [31], the correlator $\Phi_q$ (and similarly $\overline{\Phi}_q$) can be split into two parts, $\Phi_q^{[+(\Box^\dagger)]} = \Phi_q^{[+]} + \delta\Phi_q^{[+(\Box^\dagger)]}$, where the non-universal part $\delta\Phi_q$ vanishes upon $p_T$-integration or $p_T$-weighting. In what follows we will omit these non-universal parts, but in principle they could contribute (and potentially spoil factorization as recently discussed in Refs [35, 36, 37]) when one considers cross sections that are differential in measured transverse momenta. Ideally one should consider performing the appropriate weighting to remove their possible contributions altogether. We, however, keep the expressions for the cross sections differential because the weighting is often difficult in experimental data analyses and the relation with the Drell-Yan expressions is more straightforward. After weighting one would be left only with the TMD functions $\Phi_q^{[\pm]}$ and $\overline{\Phi}_q^{[\pm^\dagger]}$, in which the gauge link determines the sign with which T-odd functions are multiplied, giving in $q\bar{q}$ scattering for $h_1^{\perp q}$ a positive sign from $\Phi_q^{[+]}$ and a negative sign from $\Phi_q^{[-]}$. If no factors arise from the other correlators one sees that in SSA involving only one T-odd function $h_1^{\perp q}$, this function appears in photon-jet production with the abovementioned factor $(N^2+1)/(N^2-1)$ but otherwise the normal partonic cross section. This factor and similar ones for other T-odd functions were used in Ref. [27]. In the present case of a product of two T-odd functions, we obtain from both combinations of correlators $\Phi_q^{[+]} \otimes \overline{\Phi}_q^{[+^\dagger]}$ and $\Phi_q^{[-]} \otimes \overline{\Phi}_q^{[-^\dagger]}$ in Eq. (12) now a positive sign. Hence, the contribution $h_1^{\perp q}\, h_1^{\perp \bar{q}}$ appears with just a factor $+1$, justifying the use of the parametrizations in Eqs (8) and (9) in combination with the normal partonic hard scattering amplitudes squared. For the contribution involving the T-even gluon function $h_1^{\perp g}$ no process dependent color factors need to be considered.

The issue of factorization is left as an open question and the same applies to resummation. In Refs [38, 39] the resummation for the $\cos 2\phi$ asymmetry is addressed and found to be unclear beyond the leading logarithmic approximation. A similar situation could apply to the asymmetry in the photon-jet production case, but we will not address this here. Our present goal is to point out how the contribution of $h_1^{\perp q}\, h_1^{\perp \bar{q}}$ enters the asymmetry expression in leading order and to give an estimate of its expected magnitude.

In order to derive an expression for the cross section in terms of parton distributions, we insert the parametrizations (8)-(10) of the TMD quark, antiquark and gluon correlators into (7). Furthermore, utilizing the decompositions of the parton momenta in (4), the $\delta$-function in (7) can be rewritten as

$$\begin{aligned}\delta^4(p_1+p_2-k_1-k_2) \;=\; & \frac{2}{s}\,\delta\!\left(x_1 - \frac{1}{\sqrt{s}}\big(\,|\boldsymbol{K}_{\gamma\perp}|\,e^{\eta_\gamma} + |\boldsymbol{K}_{j\perp}|\,e^{\eta_j}\,\big)\right)\delta\!\left(x_2 - \frac{1}{\sqrt{s}}\big(\,|\boldsymbol{K}_{\gamma\perp}| e^{-\eta_\gamma} + |\boldsymbol{K}_{j\perp}|\,e^{-\eta_j}\,\big)\right)\\ & \times \delta^2(\boldsymbol{p}_{1\perp} + \boldsymbol{p}_{2\perp} - \boldsymbol{K}_{\gamma\perp} - \boldsymbol{K}_{j\perp})\;,\end{aligned} \tag{14}$$

with corrections of order $\mathcal{O}(1/s^2)$. After integration over $x_1$ and $x_2$, which fixes the parton momentum fractions by the first two $\delta$-functions on the r.h.s. of (14), the resulting hadronic cross section consists of two contributions, *i.e.*

$$\frac{d\sigma^{h_1 h_2 \to \gamma \mathrm{jet} X}}{d\eta_\gamma\, d^2\boldsymbol{K}_{\gamma\perp}\, d\eta_j\, d^2\boldsymbol{K}_{j\perp}\, d^2\boldsymbol{q}_\perp} = \frac{d\sigma[f_1^{q,g}]}{d\eta_\gamma\, d^2\boldsymbol{K}_{\gamma\perp}\, d\eta_j\, d^2\boldsymbol{K}_{j\perp}\, d^2\boldsymbol{q}_\perp} + \frac{d\sigma[h_1^{\perp\, q}]}{d\eta_\gamma\, d^2\boldsymbol{K}_{\gamma\perp}\, d\eta_j\, d^2\boldsymbol{K}_{j\perp}\, d^2\boldsymbol{q}_\perp}\,, \tag{15}$$

with $\boldsymbol{q}_\perp \equiv \boldsymbol{K}_{\gamma\perp} + \boldsymbol{K}_{j\perp}$. We are interested in events in which the photon and jet are approximately back-to-back in the transverse plane, therefore $|\boldsymbol{q}_\perp| \ll |\boldsymbol{K}_{\gamma\perp}|, |\boldsymbol{K}_{j\perp}|$. The cross section $d\sigma[f_1^{q,g}]$ depends on the unpolarized (anti)quark

and gluon distributions $f_1^{q,g}$, while $d\sigma[h_1^{\perp\,q}]$ depends on the (anti)quark function $h_1^{\perp\,q}$. More explicitly,

$$\begin{aligned}\frac{d\sigma[f_1^{q,g}]}{d\eta_\gamma\, d^2\boldsymbol{K}_{\gamma\perp}\, d\eta_j\, d^2\boldsymbol{K}_{j\perp}\, d^2\boldsymbol{q}_\perp} \;&=\; \frac{\alpha\alpha_s}{s\boldsymbol{K}_{\gamma\perp}^2}\,\delta^2(\boldsymbol{q}_\perp-\boldsymbol{K}_{\gamma\perp}-\boldsymbol{K}_{j\perp})\sum_q e_q^2\int d^2\boldsymbol{p}_{1\perp}\,d^2\boldsymbol{p}_{2\perp}\delta^2(\boldsymbol{p}_{1\perp}+\boldsymbol{p}_{2\perp}-\boldsymbol{q}_\perp)\\
&\times\bigg\{\frac{1}{N}\,(1-y)(1+y^2)\,f_1^q(x_1,\boldsymbol{p}_{1\perp}^2)f_1^g(x_2,\boldsymbol{p}_{2\perp}^2)\\
&+\frac{1}{N}\,y(1+(1-y)^2)f_1^q(x_2,\boldsymbol{p}_{2\perp}^2)f_1^g(x_1,\boldsymbol{p}_{1\perp}^2)+\frac{N^2-1}{N^2}\Big[(y^2+(1-y)^2)\\
&\times(f_1^q(x_1,\boldsymbol{p}_{1\perp}^2)f_1^{\bar q}(x_2,\boldsymbol{p}_{2\perp}^2)+f_1^q(x_2,\boldsymbol{p}_{2\perp}^2)f_1^{\bar q}(x_1,\boldsymbol{p}_{1\perp}^2))\Big]\bigg\}\,, \end{aligned}\tag{16}$$

and

$$\begin{aligned}\frac{d\sigma[h_1^{\perp\,q}]}{d\eta_\gamma\, d^2\boldsymbol{K}_{\gamma\perp}\, d\eta_j\, d^2\boldsymbol{K}_{j\perp}\, d^2\boldsymbol{q}_\perp} \;&=\; -\frac{2\alpha\alpha_s}{s\boldsymbol{K}_{\gamma\perp}^2}\,\delta^2(\boldsymbol{q}_\perp-\boldsymbol{K}_{\gamma\perp}-\boldsymbol{K}_{j\perp})\sum_q e_q^2\int d^2\boldsymbol{p}_{1\perp}\,d^2\boldsymbol{p}_{2\perp}\delta^2(\boldsymbol{p}_{1\perp}+\boldsymbol{p}_{2\perp}-\boldsymbol{q}_\perp)\\
&\times\frac{y(1-y)}{M_1M_2}\bigg((\boldsymbol{p}_{1\perp}\cdot\boldsymbol{p}_{2\perp})+\frac{(\boldsymbol{K}_{\gamma\perp}\cdot\boldsymbol{p}_{1\perp})(\boldsymbol{K}_{j\perp}\cdot\boldsymbol{p}_{2\perp})+(\boldsymbol{K}_{\gamma\perp}\cdot\boldsymbol{p}_{2\perp})(\boldsymbol{K}_{j\perp}\cdot\boldsymbol{p}_{1\perp})}{\boldsymbol{K}_{\gamma\perp}^2}\bigg)\\
&\times\frac{N^2-1}{N^2}(h_1^{\perp\,q}(x_1,\boldsymbol{p}_{1\perp}^2)h_1^{\perp\,\bar q}(x_2,\boldsymbol{p}_{2\perp}^2)+h_1^{\perp\,q}(x_2,\boldsymbol{p}_{2\perp}^2)h_1^{\perp\,\bar q}(x_1,\boldsymbol{p}_{1\perp}^2))\bigg\}\,,\end{aligned}\tag{17}$$

where the sums always run over quarks and antiquarks. Power-suppressed terms of the order $\mathcal{O}(1/(\boldsymbol{K}_{\gamma\perp}^4 s))$, such as the ones proportional to the gluon distribution function $h_1^{\perp\,g}$, are neglected throughout this paper. If we define the function

$$\begin{aligned}\mathcal{H}(x_1,x_2,\boldsymbol{q}_\perp^2)\;&\equiv\;\frac{1}{M_1M_2}\sum_q e_q^2\int d^2\boldsymbol{p}_{1\perp}\,d^2\boldsymbol{p}_{2\perp}\delta^2(\boldsymbol{p}_{1\perp}+\boldsymbol{p}_{2\perp}-\boldsymbol{q}_\perp)\Big(2(\hat{\boldsymbol{h}}_\perp\cdot\boldsymbol{p}_{1\perp})(\hat{\boldsymbol{h}}_\perp\cdot\boldsymbol{p}_{2\perp})-(\boldsymbol{p}_{1\perp}\cdot\boldsymbol{p}_{2\perp})\Big)\\
&\times(h_1^{\perp q}(x_1,\boldsymbol{p}_{1\perp}^2)h_1^{\perp\bar q}(x_2,\boldsymbol{p}_{2\perp}^2)+h_1^{\perp q}(x_2,\boldsymbol{p}_{2\perp}^2)h_1^{\perp\bar q}(x_1,\boldsymbol{p}_{1\perp}^2))\,,\end{aligned}\tag{18}$$

with $\hat{\boldsymbol{h}}\equiv\boldsymbol{q}_\perp/|\boldsymbol{q}_\perp|$, and denote with $\phi_\gamma$, $\phi_j$ and $\phi_\perp$ the azimuthal angles, in the hadronic center-of-mass frame, of the outgoing photon, jet and vector $\boldsymbol{q}_\perp$ respectively, then (17) can be rewritten as

$$\begin{aligned}\frac{d\sigma[h_1^{\perp\,q}]}{d\eta_\gamma\, d^2\boldsymbol{K}_{\gamma\perp}\, d\eta_j\, d^2\boldsymbol{K}_{j\perp}\, d^2\boldsymbol{q}_\perp}\;&=\;-\frac{2\alpha\alpha_s}{s\boldsymbol{K}_{\gamma\perp}^2}\,y(1-y)\,\frac{N^2-1}{N^2}\delta^2(\boldsymbol{q}_\perp-\boldsymbol{K}_{\gamma\perp}-\boldsymbol{K}_{j\perp})\\
&\times\sum_{l,m=1}^{2}\frac{\boldsymbol{K}_{\gamma\perp}^{\{l}\boldsymbol{K}_{j\perp}^{m\}}}{2\,\boldsymbol{K}_{\gamma\perp}^2}\bigg(\frac{\boldsymbol{q}_\perp^{\{l}\boldsymbol{q}_\perp^{m\}}}{\boldsymbol{q}_\perp^2}-\delta^{lm}\bigg)\mathcal{H}(x_1,x_2,\boldsymbol{q}_\perp^2)\\
&=\;-\frac{2\alpha\alpha_s}{s\boldsymbol{K}_{\gamma\perp}^2}\,y(1-y)\,\frac{N^2-1}{N^2}\,\delta^2(\boldsymbol{q}_\perp-\boldsymbol{K}_{\gamma\perp}-\boldsymbol{K}_{j\perp})\\
&\times\,\cos(2\phi_\perp-\phi_\gamma-\phi_j)\mathcal{H}(x_1,x_2,\boldsymbol{q}_\perp^2).\end{aligned}\tag{19}$$

The approximation $|\boldsymbol{K}_{\gamma\perp}|\approx|\boldsymbol{K}_{j\perp}|$ has been used in the derivation of the second equation in (19). Furthermore, the same approximation allows us to derive the following relations, starting from the definition of $\boldsymbol{q}_\perp$ in terms of $\boldsymbol{K}_{\gamma\perp}$ and $\boldsymbol{K}_{j\perp}$,

$$\begin{aligned}\frac{|\boldsymbol{q}_\perp|}{|\boldsymbol{K}_{\gamma\perp}|}\cos\phi_\perp\;&=\;\cos\phi_\gamma+\cos\phi_j\,,\\
\frac{|\boldsymbol{q}_\perp|}{|\boldsymbol{K}_{\gamma\perp}|}\sin\phi_\perp\;&=\;\sin\phi_\gamma+\sin\phi_j\,.\end{aligned}\tag{20}$$

Since $|\boldsymbol{q}_\perp|\ll|\boldsymbol{K}_{\gamma\perp}|$, (20) implies $\cos\phi_j\approx-\cos\phi_\gamma$ and $\sin\phi_j\approx-\sin\phi_\gamma$, so that

$$\cos(2\phi_\perp-\phi_\gamma-\phi_j)\approx-\cos2(\phi_\perp-\phi_\gamma)\approx-\cos2(\phi_\perp-\phi_j)\,,\tag{21}$$

and (19) takes the form

$$\frac{d\sigma[h_1^{\perp\,q}]}{d\eta_\gamma\, d^2\boldsymbol{K}_{\gamma\perp}\, d\eta_j\, d^2\boldsymbol{K}_{j\perp}\, d^2\boldsymbol{q}_\perp}\;=\;\frac{2\alpha\alpha_s}{s\boldsymbol{K}_{\gamma\perp}^2}\,y(1-y)\,\frac{N^2-1}{N^2}\,\delta^2(\boldsymbol{q}_\perp-\boldsymbol{K}_{\gamma\perp}-\boldsymbol{K}_{j\perp})\cos2(\phi_\perp-\phi_j)\mathcal{H}(x_1,x_2,\boldsymbol{q}_\perp^2)\,.\tag{22}$$

Substituting (16) and (22) into (15), and integrating over $\boldsymbol{K}_{j\perp}$ (alternatively, integrating over $\boldsymbol{K}_{\gamma\perp}$ would lead to the same equations as presented below, but with the replacement $\boldsymbol{K}_{\gamma\perp} \leftrightarrow \boldsymbol{K}_{j\perp}$), we obtain

$$\begin{aligned}
\frac{d\sigma^{h_1 h_2\to\gamma \mathrm{jet} X}}{d\eta_\gamma\, d\eta_j\, d^2\boldsymbol{K}_{\gamma\perp}\, d^2\boldsymbol{q}_\perp} &= \int d^2\boldsymbol{K}_{j\perp}\, \frac{d\sigma^{h_1 h_2\to\gamma \mathrm{jet} X}}{d\eta_\gamma\, d^2\boldsymbol{K}_{\gamma\perp}\, d\eta_j\, d^2\boldsymbol{K}_{j\perp}\, d^2\boldsymbol{q}_\perp} \\
&= \frac{\alpha\alpha_s}{s\boldsymbol{K}^2_{\gamma\perp}} \left\{ \frac{1}{N}\,(1-y)(1+y^2)\,\mathcal{G}(x_1,x_2,\boldsymbol{q}^2_\perp) + \frac{1}{N}\,y(1+(1-y)^2)\,\tilde{\mathcal{G}}(x_1,x_2,\boldsymbol{q}^2_\perp) \right. \\
&\quad \left. + \frac{N^2-1}{N^2}\left[ (y^2+(1-y)^2)\mathcal{F}(x_1,x_2,\boldsymbol{q}^2_\perp) + \, 2y(1-y)\,\mathcal{H}(x_1,x_2,\boldsymbol{q}^2_\perp)\,\cos 2(\phi_\perp-\phi_\gamma)\right]\right\}
\end{aligned} \tag{23}$$

where, in analogy to (18), the following convolutions of distribution functions have been utilized:

$$\begin{aligned}
\mathcal{F}(x_1,x_2,\boldsymbol{q}^2_\perp) &\equiv \sum_q e_q^2 \int d^2\boldsymbol{p}_{1\perp}\, d^2\boldsymbol{p}_{2\perp} \delta^2(\boldsymbol{p}_{1\perp}+\boldsymbol{p}_{2\perp}-\boldsymbol{q}_\perp)(f_1^q(x_1,\boldsymbol{p}^2_{1\perp}) f_1^{\bar q}(x_2,\boldsymbol{p}^2_{2\perp}) + f_1^q(x_2,\boldsymbol{p}^2_{2\perp}) f_1^{\bar q}(x_1,\boldsymbol{p}^2_{1\perp}))\,, \\
\mathcal{G}(x_1,x_2,\boldsymbol{q}^2_\perp) &\equiv \sum_q e_q^2 \int d^2\boldsymbol{p}_{1\perp}\, d^2\boldsymbol{p}_{2\perp} \delta^2(\boldsymbol{p}_{1\perp}+\boldsymbol{p}_{2\perp}-\boldsymbol{q}_\perp) f_1^q(x_1,\boldsymbol{p}^2_{1\perp}) f_1^g(x_2,\boldsymbol{p}^2_{2\perp})\,, \\
\tilde{\mathcal{G}}(x_1,x_2,\boldsymbol{q}^2_\perp) &\equiv \sum_q e_q^2 \int d^2\boldsymbol{p}_{1\perp}\, d^2\boldsymbol{p}_{2\perp} \delta^2(\boldsymbol{p}_{1\perp}+\boldsymbol{p}_{2\perp}-\boldsymbol{q}_\perp) f_1^q(x_2,\boldsymbol{p}^2_{2\perp}) f_1^g(x_1,\boldsymbol{p}^2_{1\perp})\,.
\end{aligned} \tag{24}$$

Alternatively, equation (23) can be rewritten as

$$\frac{d\sigma^{h_1 h_2\to\gamma \mathrm{jet} X}}{d\eta_\gamma\, d\eta_j\, d^2\boldsymbol{K}_{\gamma\perp}\, d^2\boldsymbol{q}_\perp} = \frac{1}{\pi^2}\, \frac{d\sigma^{h_1 h_2\to\gamma \mathrm{jet} X}}{d\eta_\gamma\, d\eta_j\, d\boldsymbol{K}^2_{\gamma\perp}\, d\boldsymbol{q}^2_\perp} \left(1 + \mathcal{A}(y,x_1,x_2,\boldsymbol{q}^2_\perp)\,\cos 2(\phi_\perp-\phi_\gamma)\right), \tag{25}$$

with

$$\begin{aligned}
\frac{d\sigma^{h_1 h_2\to\gamma \mathrm{jet} X}}{d\eta_\gamma\, d\eta_j\, d\boldsymbol{K}^2_{\gamma\perp}\, d\boldsymbol{q}^2_\perp} &= \frac{1}{4}\int d\phi_\perp\, d\phi_\gamma\, d^2\boldsymbol{K}_{j\perp}\, \frac{d\sigma^{h_1 h_2\to\gamma \mathrm{jet} X}}{d\eta_\gamma\, d^2\boldsymbol{K}_{\gamma\perp}\, d\eta_j\, d^2\boldsymbol{K}_{j\perp}\, d^2\boldsymbol{q}_\perp} \\
&= \frac{\pi^2\alpha\alpha_s}{s\boldsymbol{K}^2_{\gamma\perp}} \left\{ \frac{1}{N}\,(1-y)(1+y^2)\,\mathcal{G}(x_1,x_2,\boldsymbol{q}^2_\perp) + \frac{1}{N}\,y(1+(1-y)^2)\,\tilde{\mathcal{G}}(x_1,x_2,\boldsymbol{q}^2_\perp) \right. \\
&\quad \left. + \frac{N^2-1}{N^2}\,(y^2+(1-y)^2)\mathcal{F}(x_1,x_2,\boldsymbol{q}^2_\perp)\right\}
\end{aligned} \tag{26}$$

and the azimuthal asymmetry

$$\mathcal{A}(y,x_1,x_2,\boldsymbol{q}^2_\perp) = \nu(x_1,x_2,\boldsymbol{q}^2_\perp)\, R(y,x_1,x_2,\boldsymbol{q}^2_\perp)\,, \tag{27}$$

where

$$\nu(x_1,x_2,\boldsymbol{q}^2_\perp) = \frac{2\,\mathcal{H}(x_1,x_2,\boldsymbol{q}^2_\perp)}{\mathcal{F}(x_1,x_2,\boldsymbol{q}^2_\perp)} \tag{28}$$

contains the dependence on $h_1^{\perp\, q}$ and is identical to the azimuthal asymmetry expression that appears in the Drell-Yan process [16], with the scale $Q$ equal to $|\boldsymbol{K}_{\gamma\perp}|$. The ratio

$$\begin{aligned}
R &= \frac{\pi^2\alpha\alpha_s}{s\boldsymbol{K}^2_{\gamma\perp}}\, y(1-y)\,\mathcal{F}(x_1,x_2,\boldsymbol{q}^2_\perp) \left(\frac{d\sigma^{h_1 h_2\to\gamma \mathrm{jet} X}}{d\eta_\gamma\, d\eta_j\, d\boldsymbol{K}^2_{\gamma\perp}\, d\boldsymbol{q}^2_\perp}\right)^{-1} \\
&= \frac{N^2\, y(1-y)\,\mathcal{F}(x_1,x_2,\boldsymbol{q}^2_\perp)}{N\,(1-y)(1+y^2)\,\mathcal{G}(x_1,x_2,\boldsymbol{q}^2_\perp) + N\,y(1+(1-y)^2)\,\tilde{\mathcal{G}}(x_1,x_2,\boldsymbol{q}^2_\perp) + (N^2-1)\,(y^2+(1-y)^2)\mathcal{F}(x_1,x_2,\boldsymbol{q}^2_\perp)}
\end{aligned} \tag{29}$$

only depends on the T-even distribution functions $f_1^{q,g}(x,\boldsymbol{p}^2_\perp)$.

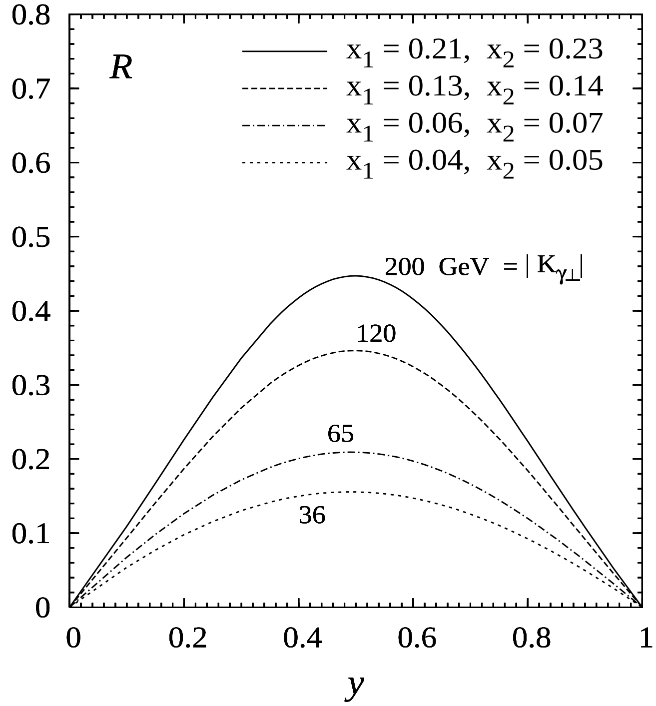


FIG. 3: The ratio $R$ defined in (29) as a function of $y$, calculated according to (35) for different values of $x_1$, $x_2$, $|\boldsymbol{K}_{\gamma\perp}|$ typical of the Tevatron experiments [40].

## III. PHENOMENOLOGY: THE AZIMUTHAL ASYMMETRY

The process $p\,\bar{p} \to \gamma\,\text{jet}\,X$ is currently being analyzed by the DØ Collaboration at the Tevatron collider [24, 40]. Data on the cross section, differential in $\eta_\gamma$, $\eta_j$ and $\boldsymbol{K}^2_{j\perp}$, have been taken at $\sqrt{s} = 1.96$ TeV, and were considered in a preliminary study [40] with the following kinematic cuts:

$$\begin{aligned} &|\boldsymbol{K}_{\gamma\perp}| > 30 \text{ GeV}\,, \qquad -1 < \eta_\gamma < 1 \;\; \text{(central region)} \\ &|\boldsymbol{K}_{j\perp}| > 15 \text{ GeV}\,, \qquad -0.8 \le \eta_j \le 0.8 \;\; \text{(central)}\,, \qquad 1.5 < |\eta_j| < 2.5 \;\; \text{(forward)}; \end{aligned} \tag{30}$$

the transverse momentum imbalance between the photon and the jet being constrained by the relation

$$|\boldsymbol{q}_\perp| < 12.5 + 0.36 \times |\boldsymbol{K}_{\gamma\perp}| \text{ (GeV)}\ . \tag{31}$$

Such angular integrated measurements are only sensitive to the transverse momentum integrated parton distributions

$$f_1^{q,g}(x) = \int d\boldsymbol{p}^2_\perp \, f_1^{q,g}(x, \boldsymbol{p}^2_\perp)\ , \tag{32}$$

as can be seen from the leading order expression of the cross section,

$$\begin{aligned} \frac{d\sigma^{p\bar{p}\to\gamma\text{jet}X}}{d\eta_\gamma\, d\eta_j\, d\boldsymbol{K}^2_{\gamma\perp}} \;=\; \frac{\pi\alpha\alpha_s}{s\boldsymbol{K}^2_{\gamma\perp}} \sum_q e_q^2 \Big\{ &\frac{1}{N}\,(1-y)(1+y^2)\, f_1^q(x_1) f_1^g(x_2) + \frac{1}{N}\, y(1+(1-y)^2) f_1^q(x_2) f_1^g(x_1) \\ &+2\frac{N^2-1}{N^2}(y^2+(1-y)^2) f_1^q(x_1) f_1^q(x_2) \Big\}\,, \end{aligned} \tag{33}$$

obtained after integrating (26), together with the definitions in (24), over $\boldsymbol{q}^2_\perp$. Here we have used that the antiquark contribution in the antiproton equals the quark contribution inside a proton. A study of the angular dependent cross section in (25) will provide valuable information on the TMD distribution function $h_1^{\perp\,q}(x, \boldsymbol{p}^2_\perp)$, if the azimuthal asymmetry $\mathcal{A}$ turns out to be sufficiently sizeable in the available kinematic region. Model calculations [10, 18] applied to the $p\,\bar{p}$ Drell-Yan process have shown that the quantity $\nu$ in (27) is of the order of 30% or higher for $|\boldsymbol{q}_\perp|$ of a few

GeV and $Q$ values of $\mathcal{O}(1-10)$ GeV. Therefore, a study of the order of magnitude of $\mathcal{A}$ as a function of $x_1$, $x_2$ and $\boldsymbol{q}_\perp^2$ requires an estimate of the ratio $R$ defined in (29). This will be obtained as follows.

First of all, the unknown TMD distribution functions appearing in (29) are evaluated assuming a factorization of their transverse momentum dependence (see, for example, [41, 42]), that is

$$f_1^{q,g}(x,\boldsymbol{p}_\perp^2) = f_1^{q,g}(x)\mathcal{T}(\boldsymbol{p}_\perp^2)\ , \tag{34}$$

with $f_1^{q,g}(x)$ being the usual unpolarized parton distributions and $\mathcal{T}(\boldsymbol{p}_\perp^2)$ being a generic function, taken to be the same for all partons and often chosen to be Gaussian. The $\boldsymbol{q}_\perp^2$-dependence of $R$ then drops out and (29) takes the form

$$R = \frac{2N^2 y(1-y)\sum_q e_q^2\, f_1^q(x_1)f_1^q(x_2)}{\sum_q e_q^2\{N(1-y)(1+y^2)f_1^q(x_1)f_1^g(x_2) + Ny(1+(1-y)^2)f_1^q(x_2)f_1^g(x_1) + 2\,(N^2-1)(y^2+(1-y)^2)f_1^q(x_1)f_1^q(x_2)\}}\ . \tag{35}$$

We consider only light quarks, *i.e.* the sum in (35) runs over $q = u$, $\bar{u}$, $d$, $\bar{d}$, $s$, $\bar{s}$, and we use the leading order GRV98 set [43] for the parton distributions, at the scale $\mu^2 = \boldsymbol{K}_{\gamma\perp}^2$.

Our results for $R$ as a function of $y$ are shown in Fig. 3 at some fixed values of the variables $x_1$, $x_2$ and $|\boldsymbol{K}_{\gamma\perp}|$, typical of the Tevatron experiments [40]. The values of $x_1$ and $x_2$ considered correspond to their average when both the photon and the jet are in the central rapidity region, where $\eta_j \approx \eta_\gamma \approx 0$ and $x_1 \approx x_2$. In this case $y \approx 0.5$, where $R$ turns out to be largest. Evidently, $R$ increases as $x_1$ and $x_2$ increase, due to the small contribution, in the denominator, of the gluon distributions $f_1^g(x)$ in the valence region.

Hence, we see that the asymmetry $\mathcal{A}$ is a product of a large Drell-Yan asymmetry term $\nu$ and a factor $R$ that is estimated to be in the 10%-50% range for Tevatron kinematics. This leads us to conclude that an asymmetry $\mathcal{A}$ in the order of 5%-15% is possible in the central region. This could allow a study of the distribution function $h_1^{\perp\, q}$ in $p\,\bar{p} \to \gamma\,\mathrm{jet}\,X$ at the Tevatron.

## IV. SUMMARY AND CONCLUSIONS

In this paper we have calculated the cross section of the process $p\,\bar{p} \to \gamma\,\mathrm{jet}\,X$ within a generalized factorization scheme, taking into account the transverse momentum of the partons in the initial proton and antiproton. In particular, we have studied the contribution from the T-odd, spin and transverse momentum dependent parton distribution $h_1^{\perp\, q}$, which leads to an azimuthal asymmetry similar to the one observed in the Drell-Yan process. Based on the fact that the latter asymmetry is large in $\pi^- N$ scattering and therefore most likely also in $p\,\bar{p}$ collisions, we have obtained an estimate for the analogous asymmetry in photon-jet production. The latter asymmetry is expected to be a factor of 2-10 smaller for typical Tevatron kinematics, which may still be sufficiently large to be measurable. This would offer a new possibility of measuring T-odd effects using this high energy collider. A similar measurement could be performed at $p\,p$ colliders as well, however, there one expects a significantly smaller contribution due to the absence of valence antiquarks.

The asymmetry measurement itself requires the reconstruction of both the length and the direction of the photon and jet momenta transverse to the beam. The angular asymmetry is then a $\cos 2\phi$ asymmetry, with the angle $\phi$ given by the difference between the angle of either one of the two transverse momenta, $\boldsymbol{K}_{j\perp}$ or $\boldsymbol{K}_{\gamma\perp}$, and the angle of their sum, $\boldsymbol{q}_\perp = \boldsymbol{K}_{j\perp} + \boldsymbol{K}_{\gamma\perp}$. Realizing the fact that the uncertainty in the latter angle $\phi_\perp$ may be rather large when relatively small $|\boldsymbol{q}_\perp|$ values are considered, it may, as an initial step, be convenient to integrate the angular distribution over four quadrants which can then be added and subtracted in the appropriate way to gain statistics. The asymmetry is found to be largest in the central rapidity region, where $\eta_j \approx \eta_\gamma \approx 0$.

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